THE PROCESS COMPUTER PROGRAM
USER'S MANUAL

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Prepared for:

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1. INTRODUCTION

The PROCESS computer program, developed by Enermodal Engineering Limited for Public Works Canada, can be used to simulate the performance of liquid-based industrial process solar water heating systems. In particular the program can be used to analyse four system types:

1) no storage tank or heat exchanger (i.e. process water flows directly through the collectors),
2) no storage tank, external heat exchanger between collector loop and process water,
3) storage tank with collector side immersed coil heat exchanger,
4) storage tank with external heat exchanger between collector loop and storage tank.

There is no limit on the size of system that can be analysed.

PROCESS is the only commercially available computer program for simulating all types of thermosyphon systems. It calculates thermal performances on a short time step (less than one hour) in order to ensure maximum accuracy. No monthly correlating equations are used.

The PROCESS computer program will provide an accurate estimate of thermal performance of industrial process solar water heating systems provided that the user supplies realistic system parameters.

2. THE PROCESS COMPUTER PROGRAM

2.1 System Descriptions

The PROCESS computer program can simulate the performance of four types of solar process and domestic hot water heating systems. Process water heating differs from other heating applications in that water use is fairly constant every day. This means that the solar storage tank can be eliminated or made very small with little loss in performance. The four systems that the program can simulate are:

1) no storage tank or heat exchanger (i.e. process water flows directly through the collectors),
2) no storage tank, external heat exchanger between collector loop and process water,
3) storage tank with collector side immersed coil heat exchanger,
4) storage tank with external heat exchanger between collector loop and storage tank.

The operation of each of these systems is discussed in the following sections.

2.1.1 System Type 1: Zero Storage, No Heat Exchanger

This is the simplest system (see Figure 2.1). City mains water flows either directly to the auxiliary tank or, if there is sufficient solar radiation, through the solar collectors first. The routing of water flow is determined by the temperature difference between the collector and the mains water and is controlled by four solenoid valves. If the collector temperature is greater than the mains water temperature, valves 1 and 2 open and valves 3 and 4 close. Water flows through the collector to the auxiliary heater and the load. No pump is needed, since the city water pressure forces the water through the collectors. It should be noted that the performance of the collectors varies with the water flow rate. If the collector temperature goes below the mains water temperature, valves 1 and 2 close and valves 3 and 4 open. In this arrangement city water goes directly to the heater and water in the collectors drains out.

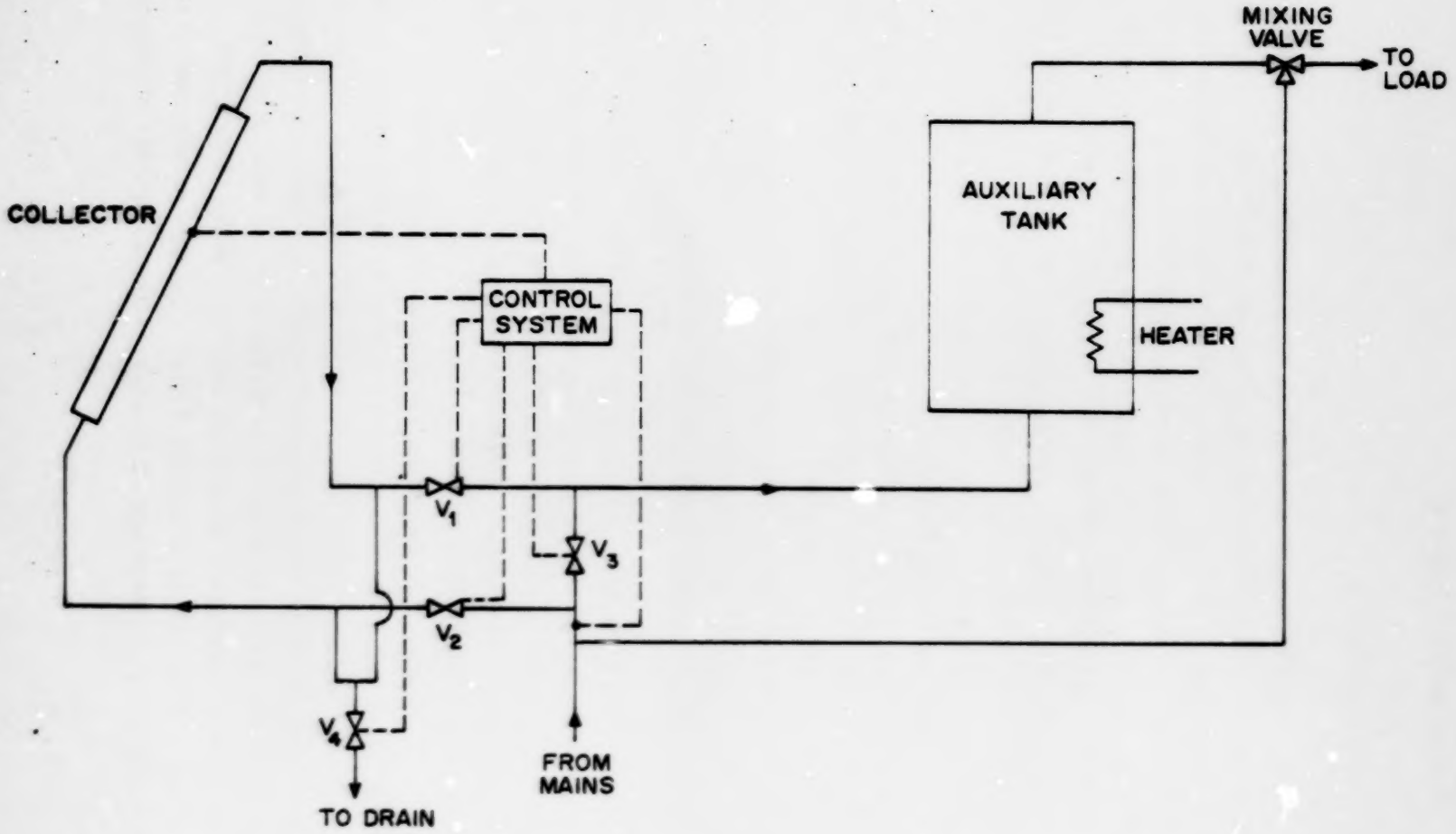


Figure 2.1: System Type 1 Schematic

If the temperature of the water delivered from the auxiliary tank is greater than the desired hot water temperature, the mixing valve will partially open. This allows cold mains water to mix with the hot auxiliary tank water to achieve the desired temperature.

This type of system is well suited for applications where there is a continuous water demand during daylight hours. If there is no load during part of the day, solar energy goes uncollected because there is no storage capability.

2.1.2 System Type 2: Zero Storage, External Heat Exchanger

This system (see Figure 2.2) is similar to system type one except that an antifreeze solution is used in the collector loop and an external heat exchanger is used to transfer heat from the antifreeze solution to the mains water.

City mains water always flows through the heat exchanger to the load. The collector pump operates whenever the collector temperature exceeds the heat exchanger temperature. Because the heat exchanger has some thermal capacitance, it is possible to collect solar energy even when there is no mains water flow. The collector pump continues to operate until the heat exchanger reaches the collector stagnation temperature or the maximum allowable temperature (typically 99°C).

Like system type one, this type of system is well suited to applications where there is a continuous water demand during daylight hours.

2.1.3 System Type 3: Storage Tank and Immersed Coil Heat Exchanger

This system (see Figure 2.3) consists of solar collectors, a thermal storage tank and an immersed coil heat exchanger. City mains water flows through the solar storage tank before entering the auxiliary tank. The antifreeze solution in the collector loop circulates whenever the collector temperature exceeds the temperature of the bottom of the storage tank.

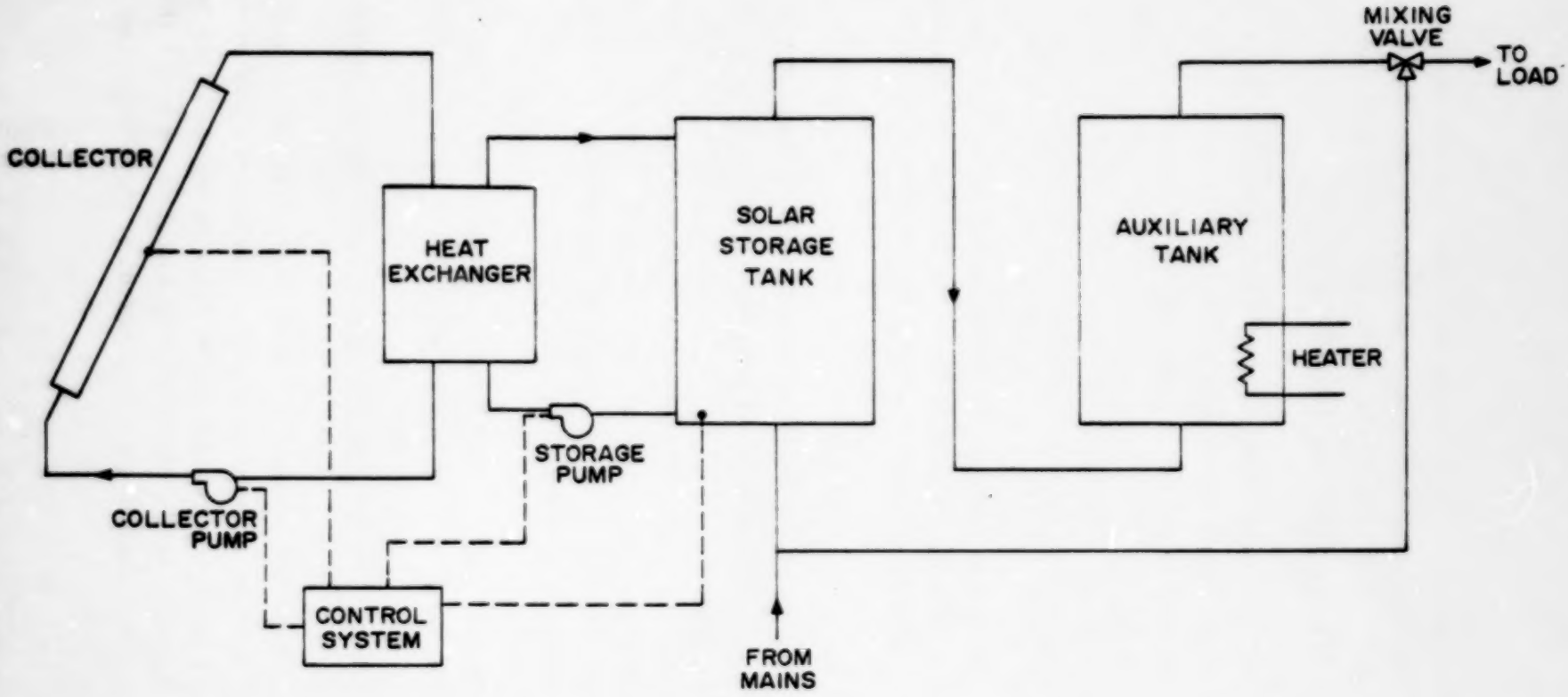


Figure 2.2: System Type 2 Schematic

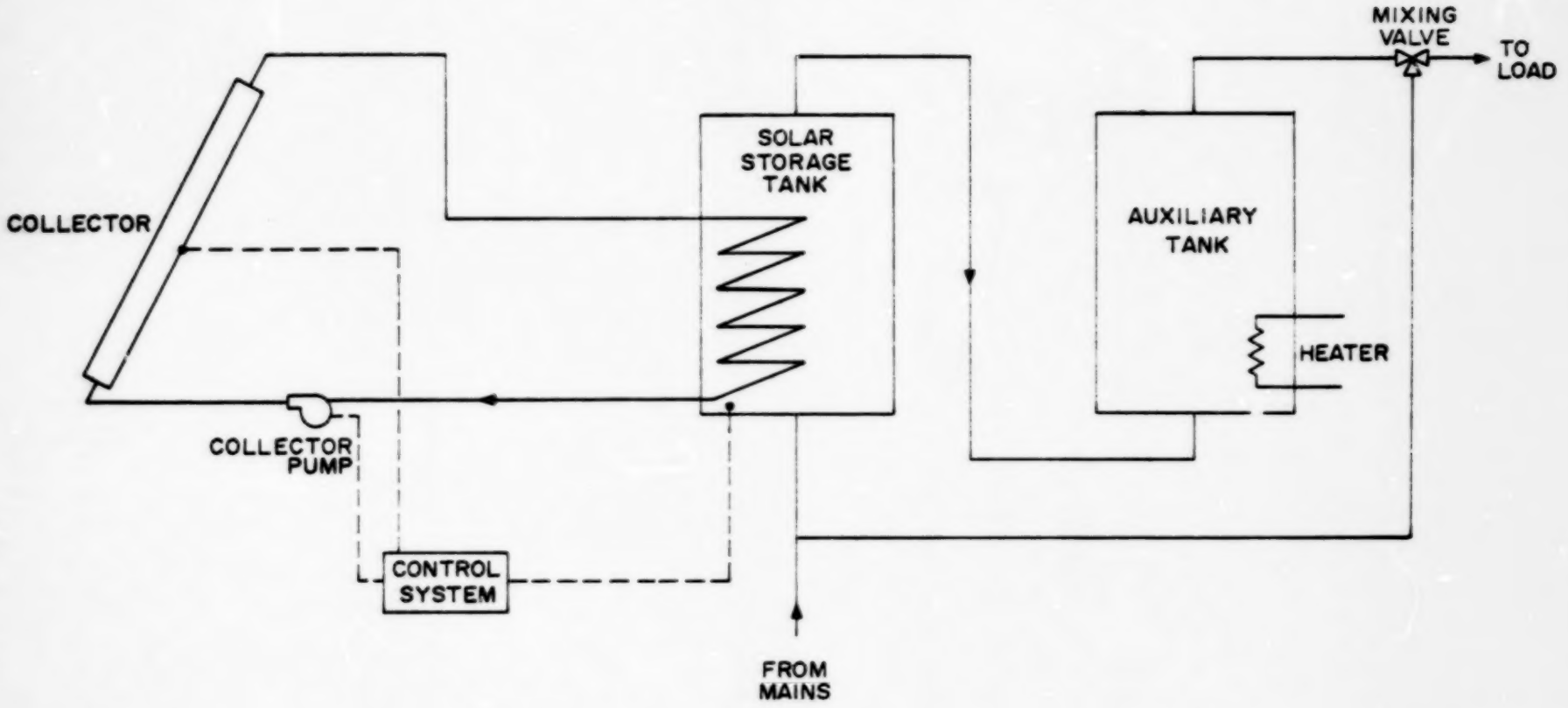


Figure 2.3: System Type 3 Schematic

The immersed coil heat exchanger transfers heat from the antifreeze solution to the water in the storage tank. If the temperature of the storage tank reaches the maximum allowable temperature (typically 99°C), the control system prevents the pump from operating.

This type of system is suited to small industrial process heating applications where the water demand is not constant. The longer the periods of no demand the larger the storage tank should be. For large collector areas, this type of system may be inefficient because of the small surface area of immersed coil heat exchangers.

2.1.4 System Type 4: Storage Tank and External Heat Exchanger

This system (see Figure 2.4) consists of solar collectors, a storage tank and an external heat exchanger. As with system type three, city mains water flows through the storage tank before entering the auxiliary tank. Whenever the collector temperature exceeds the temperature of the bottom of the storage tank, the collector and storage pumps operate. The collector pump circulates the antifreeze solution through the collectors and heat exchanger. The storage pump circulates tank water through the heat exchanger, picking up heat from the collector loop. If the storage tank temperature exceeds the maximum allowable temperature, the control system prevents the pumps from operating.

This type of system is suitable for medium and large industrial process heating systems where the water demand is not constant. Because two pumps are used, they should be properly selected to prevent excessive pump energy consumption.

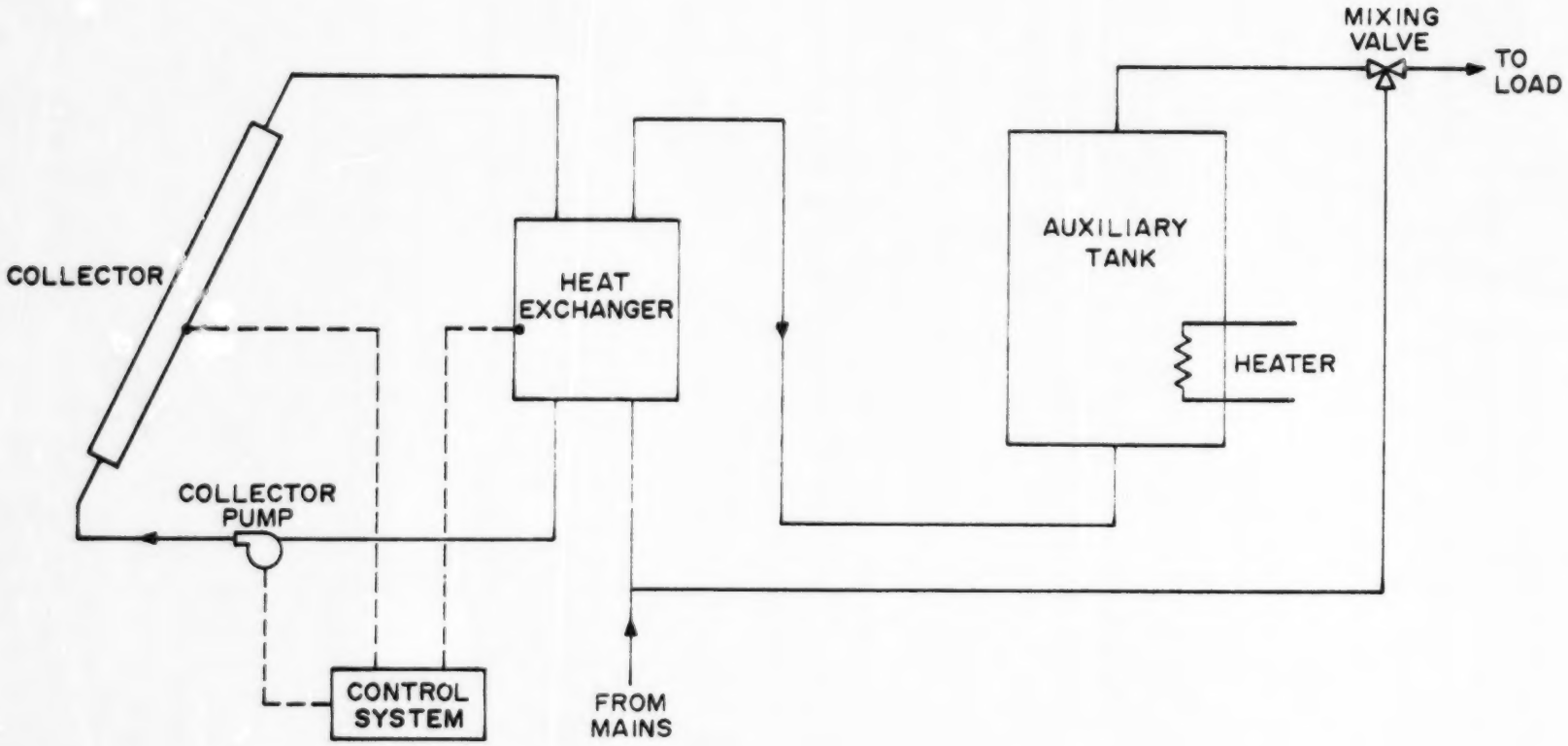


Figure 2.4: System Type 4 Schematic

2.2 Using the PROCESS Program

The PROCESS computer program is simple to use. The program has been written so that the user enters the system description interactively with the computer. The program makes some fundamental checks on the suitability of the input parameters. If a parameter appears unrealistic, a warning is printed, although the program accepts the value entered by the user.

Hourly weather data (solar radiation on a horizontal surface and ambient temperature) are required. This information can be obtained from the Atmospheric Environment Service. The first step in the program execution is to calculate solar radiation on the collector surface and store it in a scratch file which is accessed during the simulation. If the collector slope and orientation are unchanged on successive runs, the same scratch file is used. If the values are changed, the scratch file is automatically recalculated.

When the user accesses the program, a series of questions are presented and must be answered. These questions are shown in Section 5. When the questions have been answered, the user has the choice of several commands:

C or CHANGE (or CL)
D or DEFAULT
L or LIST
M or MODIFY
R or RUN
S or STOP
T or TITLE

The use of these commands is discussed below.

CHANGE This command is used to change the program input data. A list of the input data and their meanings is given in Section 3.1. The command is of the form:

C or CHANGE Parameter # = New Value

e.g. C C3 = 50

Several changes can be made on one line with or without the equal sign

e.g. C C 4 = 0.0, S1 200

The CL command changes and lists the parameter.

DEFAULT This command is used to re-initialize all the input parameters to their default values. There are no options with this parameter.

LIST This command is used to list either all the input parameters, all the parameters of one section or an individual parameter.

L or LIST ALL - lists all parameters

L C - lists all collector parameters

L C3 - lists collector slope

MODIFY This command is used to modify the system type. This command re-asks the user the questions at the beginning of the program concerning the system description.

RUN This command is used to run the program. If the option "P" is used a copy of the output will be sent to the printer. If a simulation period other than one year is required, the first day of the simulation followed by the length of the simulation should be entered

e.g. RUN or R P 31,28 - this would execute the program starting January 31st and run for 28 days. A copy of the output would be sent to the printer.

STOP This command stops the program.

TITLE This command is used to insert a title into the program output. The same title will be printed on every successive run unless it is changed.

e.g. TITLE or T THIS IS RUN NUMBER 1.

2.3 Tutorial Session

```
*****************************************
*                                       *
*              PROCESS                  *
*                                       *
*   TO SIMULATE THE PERFORMANCE OF      *
* ZERO AND LOW STORAGE SOLAR SYSTEMS    *
*       PROGRAM VERSION 1.0.            *
*            NOV 1983                   *
*                                       *
*         DEVELOPED BY:                 *
*   ENERMODAL ENGINEERING LIMITED       *
*      421 KING STREET NORTH            *
*    WATERLOO, ONTARIO N2J 4E4          *
*          (519) 884-6421               *
*                                       *
*****************************************

DO YOU WISH INSTRUCTIONS? (Y/N) : n
 IS PROCESSED WEATHER DATA AVAILABLE (Y/N) ?y

 ENTER THE IPH SOLAR HEATING SYSTEM TYPE :
    1 - ZERO STORAGE WITH NO HEAT EXCHANGER
    2 - ZERO STORAGE WITH EXTERNAL HEAT EXCHANGER
    3 - LOW STORAGE WITH IMMERSED COIL HEAT EX.
    4 - LOW STORAGE WITH EXTERNAL HEAT EXCHANGER ?1

C,D,L,M,R,S,T,?: c c1 5.
THE NUMBER OF CHANGES MADE =    1

C,D,L,M,R,S,T,?: l c1
C1   NUMBER OF COLLECTORS.............................     5.00

C,D,L,M,R,S,T,?: t sample run

C,D,L,M,R,S,T,?: c1 a8 18.
A8   AUXILIARY TANK SURROUNDING TEMPERATURE..........    18.00
THE NUMBER OF CHANGES MADE =    1

C,D,L,M,R,S,T,?: r 1,60
```

SAMPLE RUN

ZERO STORAGE, NO H.X. SOLAR IPH SYSTEM

C. COLLECTOR DATA

C1	NUMBER OF COLLECTORS	5.00
C2	COLLECTOR SLOPE (DEGREES)	45.00
C3	COLLECTOR ORIENTATION (SOUTH=0,EAST=+, DEG.)	.00
C4	FLUID : 1-WATER, 2-PROP GLYCOL, 3-ETHY GLYCOL	1.00
C5	PERCENTAGE OF FLUID THAT IS GLYCOL (%)	.00
C6	GROSS AREA OF ONE COLLECTOR (M2)	2.00
C7	FR-TAU-ALPHA (TEST)	.70
C8	FR-UL (W/(M2*C)) (TEST)	5.00
C9	COLLECTOR TEST FLOW RATE (L/MIN)	2.00
C10	COLL. TEST FLUID 1-WATER,2-PROP GLY 3-ETHY GLY	.00
C11	PERCENTAGE OF TEST FLUID THAT IS GLYCOL (%)	.00
C12	TIME CONSTANT AT TEST FLOW RATE (MIN)	2.00
C13	INCIDENT ANGLE MODIFIER	

I	: 1	2	3	4	5
THETA	: 15.000	30.000	45.000	60.000	75.000
AIT	: 1.000	1.000	.950	.830	.720

F. COLLECTOR SUPPLY AND RETURN PIPE DATA

F1	LENGTH OF COLLECTOR SUPPLY PIPE (M)	3.40
F2	PERCENTAGE OF SUPPLY PIPE LENGTH OUTDOORS (%)	100.00
F3	SUPPLY PIPE INSIDE DIAMETER (MM)	21.00
F4	RSI VALUE OF OUTDOOR SUPPLY PIPE INSUL. (M2-C/W)	2.20
F5	RSI VALUE OF INDOOR SUPPLY PIPE INSUL. (M2-C/W)	2.20
F6	LENGTH OF COLLECTOR RETURN PIPE (M)	1.20
F7	PERCENTAGE OF RETURN PIPE LENGTH OUTDOORS (%)	100.00
F8	RETURN PIPE INSIDE DIAMETER (MM)	26.00
F9	RSI VALUE OF OUTDOOR RETURN PIPE INSUL. (M2-C/W)	2.20
F10	RSI VALUE OF INDOOR RETURN PIPE INSUL. (M2-C/W)	2.20

L. WATER LOAD DATA

L1	HOT WATER SET TEMPERATURE (C)	51.00
L2	AVERAGE MAINS WATER TEMPERATURE (C)	7.00
L3	MINIMUM MAINS WATER TEMPERATURE (C)	5.00
L4	DRAW FLOW RATE, 0 = AVERAGED OVER HOUR (L/MIN)	1.00
L5	DAYS PER WEEK AT LOAD PROFILE 1	.00
L6	DAILY HOT WATER LOAD AT LOAD PROFILE 1 (L/DAY)	300.00
L7	DAILY HOT WATER LOAD AT LOAD PROFILE 2 (L/DAY)	300.00
L8	HOURLY HOT WATER PROFILE 1 (PERCENT)	100.00

.0000	.0000	.0000	.0000	.0000	.0000
4.4400	11.1100	2.2200	20.0000	2.2200	4.4400
2.2200	.0000	.0000	4.4400	11.1100	20.0000
11.1100	4.4400	2.2200	.0000	.0000	.0000

L9	HOURLY HOT WATER PROFILE 2 (PERCENT)				100.00
.0000	.0000	.0000	.0000	.0000	.0000
.0000	10.0000	10.0000	10.0000	10.0000	10.0000
10.0000	10.0000	10.0000	10.0000	10.0000	.0000
.0000	.0000	.0000	.0000	.0000	.0000

A. AUXILIARY HEATER DATA

A1	LOCATION: 1-IN SOLAR TANK, 2-IN AUX. TANK.....	2.00
A2	TEMPERING VALVE: 0 - NO, 1 - YES.....	1.00
A3	FUEL TYPE: 1- ELEC., 2 - NATURAL GAS, 3 - OIL ..	1.00
A4	SEASONAL EFFICIENCY OF AUX. HEATER (%).....	100.00
A5	VOLUME OF AUXILIARY TANK (LITRES).....	250.00
A6	DIAMETER OF AUXILIARY TANK (M).....	.50
A7	RSI VALUE OF INSULATION (M2-C/W).....	1.50
A8	AUXILIARY TANK SURROUNDING TEMPERATURE.....	19.00

CITY DATA

LOCATION AND LATITUDE.....OTTAWA 45.50

CALCULATED SYSTEM PARAMETERS

HEAT LOSS COEFFICIENTS

SOLAR STORAGE TANK (W/C) = .00
AUXILIARY TANK (W/C) = 1.54
COLL. INLET PIPE (W/C) = .34
COLL. OUTLET PIPE (W/C) = .12

THERMAL PERFORMANCE SUMMARY

MON	SOLAR AVAIL. (GJ)	SOLAR COLLECT (GJ)	SOLAR DELIVER (GJ)	SYSTEM LOSSES (GJ)	HEATING LOAD (GJ)	AUX. HEATING (GJ)	PUMP ENERGY (GJ)
JAN	3.313	.660	.655	.005	1.864	1.209	.000
FEB	3.283	.594	.589	.005	1.700	1.111	.000
MAR	.222	.050	.049	.001	.061	.015	.000
YR	7.31	1.30	1.29	.01	3.63	2.33	.00

TOTAL ENERGY CONSUMPTION OVER SIMULATION PERIOD

	EXISTING	WITH SOLAR	SAVINGS
IN GJ	3.63	2.33	1.29
IN KWHR	1007.	647.	359.

** ENERGY SAVING: 35.7 PERCENT

** MAXIMUM ENERGY INPUT (KW): 3.19
** MAXIMUM SOLAR DELIVERY TEMPERATURE (C): 84.4
** MINIMUM SOLAR DELIVERY TEMPERATURE (C): 5.0
** ENERGY GAINED BY STORAGE TANKS (GJ): .004

C,D,L,M,R,S,T,?: s
DO YOU WISH TO SAVE THE CURRENT INPUT DATA ?n

3. INPUT PARAMETERS

The following sections describe the parameters used in the PROCESS computer program. The default value for each parameter is included with the definition; these are summarized in Section 5.

3.1 Definition of Input Parameters

There are eight separate sections of input data:

C - collector data
S - storage data
I - immersed coil heat exchanger data
E - external heat exchanger data
P - collector supply and return pipe data
F - flow device data
L - water load data
A - auxiliary heater data.

The sections required for the four system types are shown below:

Section	Zero Storage, No Heat Ex.	Zero Storage, External H.X.	Storage, Immersed Coil H.X.	Storage, External H.X.
C	X	X	X	X
S			X	X
I			X	
E		X		X
P	X	X	X	X
F		X	X	X
L	X	X	X	X
A	X	X	X	X

The parameters in each of the data sections are discussed below.

Collector Data

C1 NUMBER OF COLLECTORS (2)

The number of collectors in the solar heating system.

C2 COLLECTOR SLOPE (DEGREES) (45)

The angle that the collector is tilted from the horizontal in degrees. This parameter must be between 0 and 90. If this parameter is different from the value on the scratch weather file, the weather data will automatically be reprocessed.

C3 COLLECTOR ORIENTATION (SOUTH=0 EAST=+, DEG) (0)

The number of degrees that the collector is oriented off due south (east is positive, west is negative). This parameter must be between -90 and 90. If this parameter is different from the value on the scratch weather file, then the weather data will automatically be reprocessed.

C4 FLUID 1-WATER, 2-PROP GLYCOL, 3-ETHY GLYCOL (1)

This parameter specifies the fluid to be used in the collector loop where 1 indicates water, 2 indicates a propylene glycol-water mixture and 3 indicates a ethylene glycol-water mixture.

C5 PERCENTAGE OF FLUID THAT IS GLYCOL (%) (0)

If parameter C4 is 2 or 3, this parameter is the percentage of the fluid mixture that is glycol.

C6 GROSS AREA OF ONE COLLECTOR (M2) (2)

The gross or outside area of one collector in square metres.

C7 FR-TAU-ALPHA (TEST) (0.7)

The $F_R(\tau\alpha)_e$ of the collector when tested by a certified laboratory.

C8 FR-UL (W/M°C) (TEST) (5.0)

The $F_R U_L$ of the collector when tested by a certified laboratory.

C9 COLLECTOR TEST FLOW RATE (L/M) (2)

The liquid flow rate at test conditions in litres per minute.

C10 COLLECTOR TEST FLUID 1-WATER, 2-PROP GLY, 3-ETHY GLY (1)

This parameter specifies the fluid used when the collector was tested where 1 indicates water, 2 indicates a propylene glycol-water mixture and 3 indicates a ethylene glycol-water mixture.

C11 PERCENTAGE OF TEST FLUID THAT IS GLYCOL (%) (0)

If parameter C10 is 2 or 3, this parameter is the percentage of the collector test fluid that is glycol.

C12 TIME CONSTANT AT TEST FLOW RATE (MIN) (2)

Collector time constant at test flow rate as determined by testing laboratory, typically 1 to 3 minutes.

C13 INCIDENT ANGLE MODIFIER

Five pairs of values of collector-sun incidence angle (THETA) and incident angle modifier (AKT). The angles must be between 1 and 90 degrees. If a value for 90 degrees is not specified, the program assumes an AKT of 0. By definition the AKT = 1 for an angle of zero.

Solar Storage Tank Data

S1 VOLUME OF SOLAR STORAGE TANK (LITRES) (250)

Volume of water in solar storage tank in litres.

S2 ORIENTATION: 1-HORIZONTAL, 2-VERTICAL (2)

Orientation of storage tank length or height, 1 for upright tank, 2 for tank on side.

S3 DIAMETER OF SOLAR STORAGE TANK (M) (0.5)

Inside diameter of solar storage tank in metres. The program calculates the tank height from this value and the volume.

S4 RSI VALUE OF TANK INSULATION (M2-C/W) (1.5)

Thermal resistance of the tank insulation in m^2 C/W. (1 m^2 C/W = 5.678 BTU/hrft^2°F).

S5 SURROUNDING TEMPERATURE (-100 FOR OUTDOORS) (C) (20)

The temperature of the air surrounding the storage tank, typically the building temperature for indoor storage. For outdoor storage units use a value of -100. This signals to the program that the storage heat loss is to the ambient air.

S6 LOCATION OF COLLECTOR RETURN CONNECTION (0)

The fractional distance down the tank where the collector return pipe enters the tank. If the connection is at the top of the tank, this parameter is 0.

S7 LOCATION OF COLLECTOR SUPPLY CONNECTION (1)

The fractional distance down the tank where the collector supply pipe leaves the tank. If the connection is at the bottom of the tank, this parameter is 1.

S8 LOCATION OF MAINS WATER INLET CONNECTION (1)

The fractional distance down the tank where city mains or well water enters the tank. If the connection is at the bottom of the tank, this parameter is 1.

S9 LOCATION OF MAINS WATER OUTLET CONNECTION (0)

The fractional distance down the tank where tank water leaves the tank. If the connection is at the top of the tank, this parameter is 0.

S10 MAXIMUM STORAGE TANK TEMPERATURE (C) (99)

The maximum allowable storage tank temperature in degrees Celsius. Most solar heating systems shut off if the water is in danger of boiling i.e. 99°C.

Immersed Coil Heat Exchanger Data

I1 LENGTH OF EACH COIL (M) (10)

Length of each heat exchanger coil in metres.

I2 NUMBER OF COILS (1)

Number of heat exchanger coils connected in parallel.

I3 INSIDE COIL DIAMETER (MM) (25)

Inside heat exchanger coil diameter in millimetres.

I4 OUTSIDE COIL DIAMETER (MM) (26)

Outside heat exchanger coil diameter in millimetres.

I5 NUMBER OF FINS/CM (0)

The number of annular heat exchanger fins per centimetre on the outside of the immersed coil. This parameter is not used in the wrap around heat exchanger model.

I6 LENGTH OF FINS (mm) (0)

The distance that the fin protrudes from the pipe in millimetres or the fin outside diameter minus the pipe diameter divided by two.

I7 THICKNESS OF FIN (MM) (2)

The average thickness of an individual fin in millimetres.

External Heat Exchanger Data

E1 H.X. TYPE 1-COUNTER, 2-PARALLEL, 3-COMBINED (1)

The type of heat exchanger where 1 is counter flow, 2 is parallel flow and 3 is cross flow or multi-pass shell and tube.

E2 H.X. EFFECTIVENESS AT FLOW RATES E3 AND E4 (0.5)

The effectiveness of heat exchanger at flow rates E3 and E4.

E3 SHELL SIDE TEST FLOW RATE (L/MIN) (WATER) (1.5)

The test flow rate on the shell side (i.e. what will be the load side) in litres per minute.

E4 TUBE SIDE TEST FLOW RATE (L/MIN) (1.5)

The test flow rate on the tube side (i.e. what will be the collector side) in litres per minute.

E5 H.X. TUBE TEST FLUID: 1 - WAT, 2 - PROP GLY, 3 - ETHY GLY (1)

The fluid used on the tube side when the heat exchanger was tested where 1 is pure water, 2 propylene glycol/water mixture, 3 - ethylene glycol/water mixture.

E6 PERCENTAGE OF TEST FLUID THAT IS GLYCOL (%) (0)

The percent of fluid E5 that is glycol when tested.

E7 CAPACITANCE OF HEAT EXCHANGER (KJ/C) (50)

The thermal capacitance of the heat exchanger in KJ/C. This is calculated as the mass of the heat exchanger times its specific heat plus the mass of fluid contained in the heat exchanger times the fluid specific heat.

Collector Supply and Return Pipe Data

P1 LENGTH OF COLLECTOR SUPPLY PIPE (M) (4)

Total length of collector supply pipe in metres (runs between tank outlet and collector inlet).

P2 PERCENTAGE OF SUPPLY PIPE LENGTH OUTDOORS (%)

Percentage of the collector supply pipe that is outdoors (i.e loses heat to the ambient).

P3 SUPPLY PIPE INSIDE DIAMETER (MM) (25)

Inside diameter of collector supply pipe in millimetres.

P4 RSI VALUE OF INDOOR SUPPLY PIPE INSULATION (M2-C/W) (1)

Thermal resistance of the indoor section of the collector supply pipe insulation in m^2C/W i.e. RSI value per cm times the thickness. (1 m^2C/W = 5.678 BTU/hrft^2°F).

P5 RSI VALUE OF OUTDOOR SUPPLY PIPE INSULATION (M2-C/W) (1)

Thermal resistance of the outdoor section of the collector supply pipe insulation in m^2C/W i.e. RSI value per cm times the thickness. (1 m^2C/W = 5.678 BTU/hrft^2°F).

P6 LENGTH OF COLLECTOR RETURN PIPE (M) (3)

Total length of collector return pipe in metres (runs between collector outlet and tank inlet).

P7 PERCENTAGE OF RETURN PIPE LENGTH OUTDOORS (%)

Percentage of collector return pipe that is outdoors.

P8 RETURN PIPE INSIDE DIAMETER (MM) (25)

Inside diameter of collector return pipe in millimetres.

P9 RSI VALUE OF OUTDOOR RETURN PIPE INSULATION (M2-C/W) (1)

Thermal resistance of the outdoor section of the collector return pipe insulation in m^2C/W i.e. RSI value per cm times the thickness. (1 m^2C/W = 5.678 BTU/hrft^2°F).

P10 RSI VALUE OF INDOOR RETURN PIPE INSULATION (M2-C/W)

Thermal resistance of the indoor section of the collector return pipe insulation in m^2C/W i.e. RSI value per cm times the thickness. (1 m^2C/W = 5.678 BTU/hrft^2°F).

Flow Device Data

F1 COLLECTOR PUMP FLOW RATE (L/MIN)

Desired volume flow rate in collector loop in litres/minute.

F2 COLLECTOR PUMP INPUT POWER REQUIREMENT (W) (0)

Electrical energy input to collector pump in Watts.

F3 FRACTION OF COLL. PUMP ENERGY THAT ENTERS FLUID (0.9)

Fraction of collector pump input energy that ends up in circulating fluid, typically 0.9 for water cooled pumps and 0.4 for air cooled pumps.

F4 STORAGE PUMP FLOW RATE (L/MIN)

Desired volume rate in storage loop in litres/minute.

F5 STORAGE PUMP INPUT POWER REQUIREMENT (W)

Electrical energy input to storage pump in Watts.

F6 FRACTION OF STOR. PUMP ENERGY THAT ENTERS FLUID

Fraction of storage pump input energy that ends up in circulating fluid, typically 0.9 for water cooled pumps and 0.4 for air cooled pumps.

Water Load Data

L1 HOT WATER SET TEMPERATURE (C) (50)

The desired temperature for the hot water i.e. the set point temperature for the auxiliary heater.

L2 AVERAGE MAINS WATER TEMPERATURE (C) (7)

Yearly average temperature of the city mains or well water. Typical values for this parameter are given in Section 3.2.

L3 MINIMUM MAINS WATER TEMPERATURE (C) (5)

Minimum city mains or well water temperature for the year. Typical values for this parameter are given in Section 3.2.

L4 DRAW FLOW RATE, 0 = AVERAGED OVER HOUR (L/MIN) (5)

Average water flow rate to the load in litres per minute, if set equal to zero the flow rate is adjusted each hour so that the load is continuous over the hour. See parameters L6 to L9 for load data.

L5 DAYS PER WEEK AT LOAD PROFILE 1 (7)

Number of days per week that load profile 1 is in effect i.e. weekdays.

L6 DAILY HOT WATER LOAD AT LOAD PROFILE 1 (L/DAY) (300)

Total hot water demand per day for load profile 1 (i.e. weekdays) in litres per day.

L7 DAILY HOT WATER LOAD AT LOAD PROFILE 2 (L/DAY) (0)

Total hot water demand per day for load profile 2 (i.e. weekend) in litres per day.

L8 HOURLY HOT WATER PROFILE 1 (PERCENT)

When this parameter is specified the program will prompt the user for 24 hourly percentages of daily water demand. These values must sum to 100%.

L9 HOURLY HOT WATER PROFILE 2 (PERCENT)

When this parameter is specified the program will prompt the user for 24 hourly percentages of daily water demand. These values must sum to 100%.

Auxiliary Heater Data

A1 LOCATION: 1-IN SOLAR TANK 2-IN AUX. TANK (2)

Location of the auxiliary heater where 1 indicates the heater is in the top of the solar tank and 2 indicates the heater is in the auxiliary tank.

A2 TEMPERING VALVE: 0 - NO, 1 - YES (1)

This parameter specifies whether or not a tempering valve is placed after the auxiliary tank. If yes, cold water is mixed with the hot water to achieve the desired temperature. If no, water is drawn according to the volume demand with no reduction if the water is hotter than desired.

A3 FUEL TYPE: 1-ELEC., 2-NATURAL GAS, 3-OIL (1)

The fuel used by the auxiliary heater where 1 is electricity, 2 is natural gas and 3 is #2 oil.

A4 SEASONAL EFFICIENCY OF AUX. HEATER (%) (100)

Seasonal (not instantaneous) efficiency of the auxiliary heater specified in A3. Electricity is typically 100% and natural gas and oil are typically 60-65%.

A5 VOLUME OF AUXILIARY TANK (LITRES) (250)

The volume of water in the auxiliary tank in litres.

A6 DIAMETER OF AUXILIARY TANK (M) (0.5)

Inside diameter of auxiliary tank.

A7 RSI VALUE OF TANK INSULATION (M2-C/W) (1.5)

The thermal resistance of the auxiliary tank insulation in m^2C/W i.e. the thickness times RSI per thickness. (1 m^2C/W = 5.678 $BTU/hrft^2°F$).

A8 AUXILIARY TANK SURROUNDING TEMPERATURE (C) (20)

The temperature of the air surrounding the auxiliary tank in degrees Celcius.

3.2 City Mains Water Temperature

The temperature of city mains water varies throughout the year. The city mains water temperature is generally very close in temperature to the ground. Well water would probably be at a constant temperature equal to the yearly average ground temperature. Table 3.1 gives the yearly average ground temperature and minimum ground temperature at a depth of 1.5 metres as published by Atmospheric Environment Services (A.E.S.).

Table 3.1 Ground Temperatures for Selected Canadian Locations

City	Province	Minimum Ground Temperature (°C)	Yearly Average Ground Temperature (°C)
Prince George	B.C.	2.4	6.2
Vancouver	B.C.	7.5	11.3
Summerland	B.C.	5.2	12.3
Calgary	Alta.	0.5	5.6
Regina	Sask.	2.2	4.9
Saskatoon	Sask.	0.6	6.2
Winnipeg	Man.	0.6	5.6
Kapuskasing	Ont.	2.4	6.6
Toronto	Ont.	4.5	10.3
Ottawa	Ont.	3.5	8.7
Val D'Or	Que.	1.3	6.4
Fredericton	N.B.	2.6	7.8
Charlottetown	P.E.I.	2.4	7.3
Truro	N.S.	2.6	7.7
St. John's	Nfld.	2.5	6.7
Goose	Nfld.	0.8	4.7

4. DESCRIPTION OF PROGRAM OUTPUT

The thermal analysis of the system is printed in monthly intervals with a yearly summary printed at the end. The results are an estimate of the performance of a properly designed and installed system. The program cannot account for improperly insulated piping or other system faults.

The definition of the seven monthly output values follow.

SOLAR AVAIL (GJ)

Total solar radiation incident on the collector over the time period in gigajoules.

SOLAR COLLECT (GJ)

Solar energy converted to heat by the solar collector over the time period.

SOLAR DELIVER (GJ)

Solar energy delivered to the auxiliary hot water tank over the time period.

SYSTEM LOSSES (GJ)

Heat losses from the collector piping and storage tank to the environment over the time period.

HEATING LOAD (GJ)

The auxiliary heat required over the time period to heat the water if there was no solar heating system. This value includes heat losses from the auxiliary storage tank.

AUX. HEATING (GJ)

Auxiliary energy required to heat the water over the time period when the solar heating system is used. This value includes any energy required to keep the water in the solar heating system from freezing.

PUMP ENERGY (GJ)

The electrical energy required to operate the collector and storage pumps (if used) over the time period.

After the monthly totals have been printed, the yearly sum of the seven quantities is printed. A summary of energy use and savings is then printed in gigajoules and the appropriate fuel units i.e. kWhr, cubic metres or litres.

The ENERGY SAVING is the percent reduction in auxiliary energy use attributable to the addition of the solar heating system i.e. percent solar. It is defined as

$$\text{Energy Saving (\%)} = \frac{100\ (\text{Heating Load} - \text{Aux. Heating} - \text{Pump Energy})}{\text{Heating Load}}$$

The MAXIMUM ENERGY INPUT (kW) is the maximum auxiliary energy input to bring the auxiliary water tank up to temperature within one hour of the water draw. This number is useful in sizing the auxiliary water heater.

MAXIMUM DELIVERY TEMPERATURE (C) and MINIMUM DELIVERY TEMPERATURE (C) are the maximum and minimum temperatures of the solar storage tank over the simulation period. This would also be the maximum and minimum delivery temperatures to the auxiliary tank. If an auxiliary heater and tempering valve were not used then these values would give the range of temperatures expected at the water taps. It should be noted that the program initially sets the solar storage tank temperature to the average mains water temperature. If minimum delivery temperature is equal to the initial temperature then the initial temperature might be in error.

If auxiliary energy is required to prevent water in the solar heating system from freezing the program will print the total "AUXILIARY ENERGY REQUIRED TO PREVENT FREEZING".

5. PROGRAM ALGORITHM

5.1 Overview of Program Operation

The PROCESS computer program calculates the performance of solar heating industrial process water. As shown in Section 2. the program can simulate four system configurations. The basic assumption of the program is that for the purposes of calculating performance, the performance and all variables including solar radiation can be considered constant for each time step (typically one hour). The program operation for each system is discussed below.

After all the parameters have been entered, the program calculates hourly values of solar radiation on the tilted surface. The algorithm for performing this calculation is given in Section 5.9. If on successive runs the collector slope or azimuth is changed, the tilted solar radiation is re-calculated.

5.1.1 System 1 Overview

For this system the hour is split into two parts: period of water demand and period of no water demand. The length of the period of water demand (τ_D) is found by dividing the hourly water demand by the average water flow rate (parameter L4) or

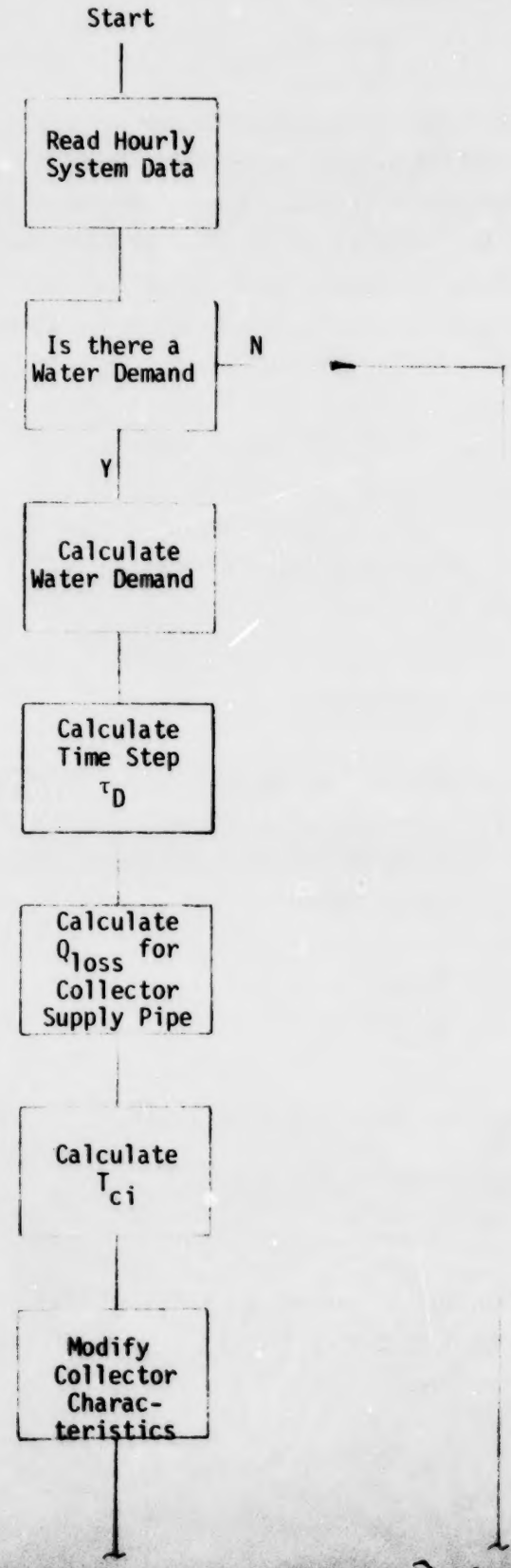
$$\tau_D = \frac{\dot{m}_{DHW}}{\dot{m}_{ave}}$$

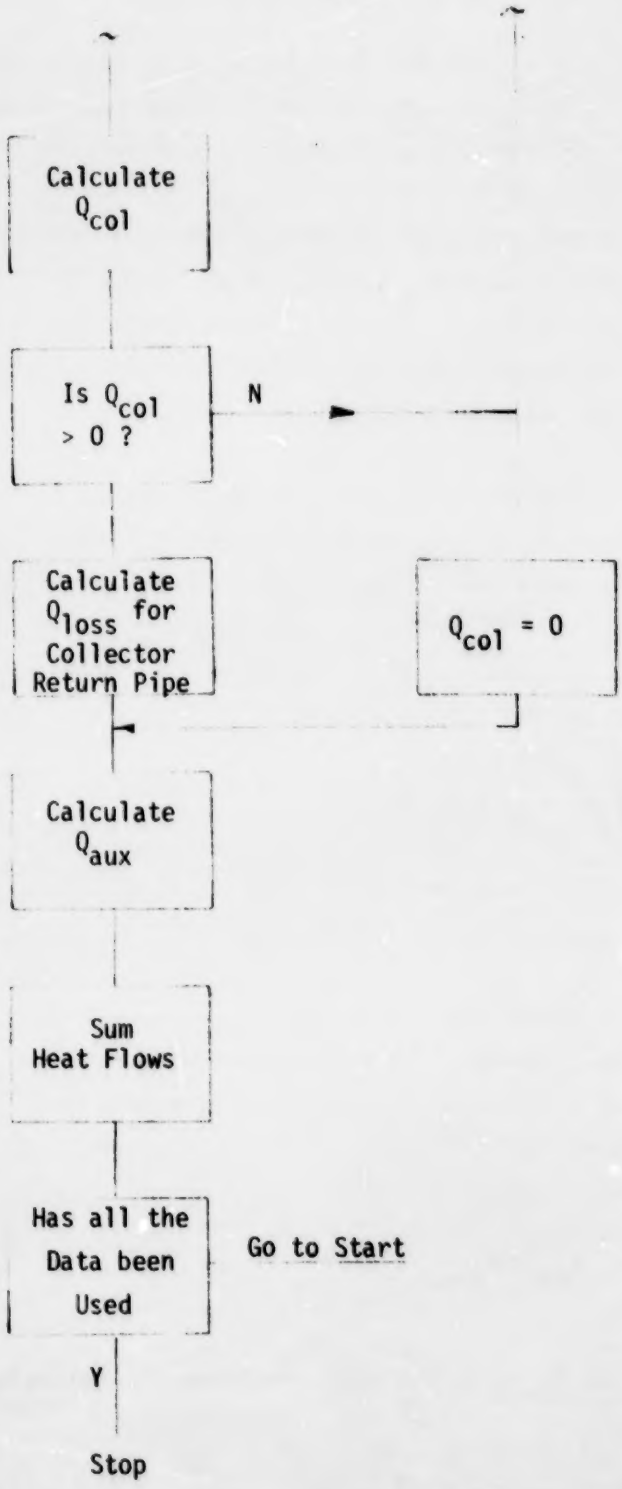
The period of no water demand is then:

$$\tau_{ND} = 1 - \tau_D$$

During the period τ_D, if solar heat can be collected, water is circulated through the collector. The inlet temperature to the collector (T_{ci}) is given by:

Figure 5.1: Program Flow Chart for System 1




Calculate Q_{col}
Is Q_{col} > 0 ?
N
Calculate Q_{loss} for Collector Return Pipe
Q_{col} = 0
Calculate Q_{aux}
Sum Heat Flows
Has all the Data been Used
Go to Start
Y
Stop

$$T_{ci} = T_{mains} - Q_{loss} / \dot{m}Cp$$

where Q_{loss} is the pipe heat loss to the environment, see Section 5.6,
T_{mains} is the city mains water temperature,
$\dot{m}Cp$ is the heat capacitance flow rate through the collector.

The collector thermal performance characteristics are modified each time step according to the water flow rate. The calculation of the collector outlet temperature is described in Section 5.2. The pipe heat loss from the collector return pipe is then calculated and the water temperature adjusted accordingly.

The amount of auxiliary heat that must be added to achieve the desired hot water temperature is then calculated (see Section 5.7). For the period of no water demand the system does not operate.

The hourly values of the above energy flows are summed and monthly totals printed.

5.1.2 System 2 Overview

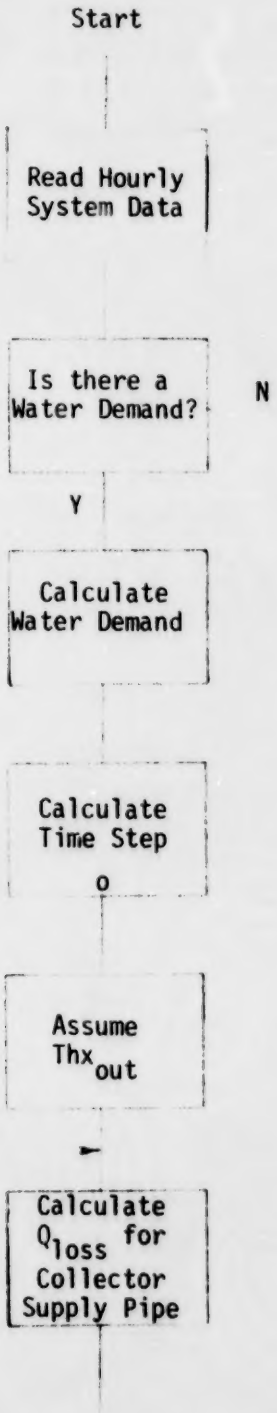
For this system the hour is also split into period of water demand (τ_D) and period of no water demand (τ_{ND}).

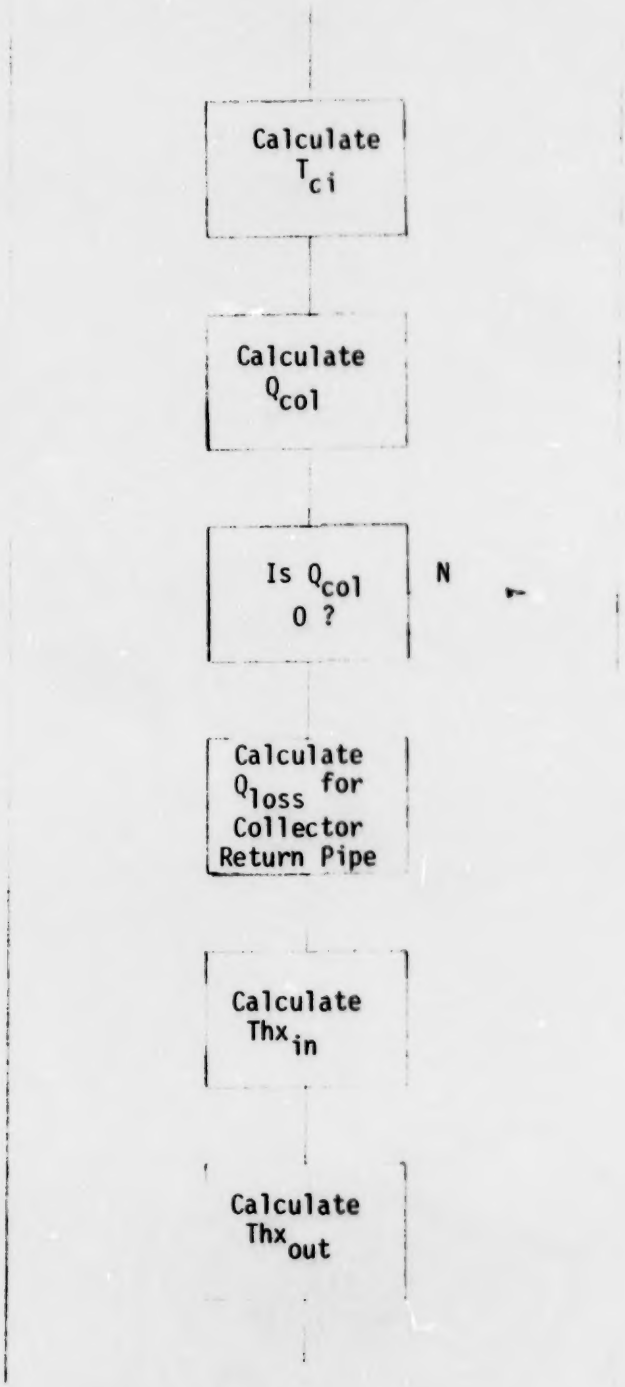
During the period τ_D, if solar heat can be collected, the collector side pump turns on. The program makes an estimate of the temperature of the collector-side fluid leaving the heat exchanger. The collector inlet temperature is:

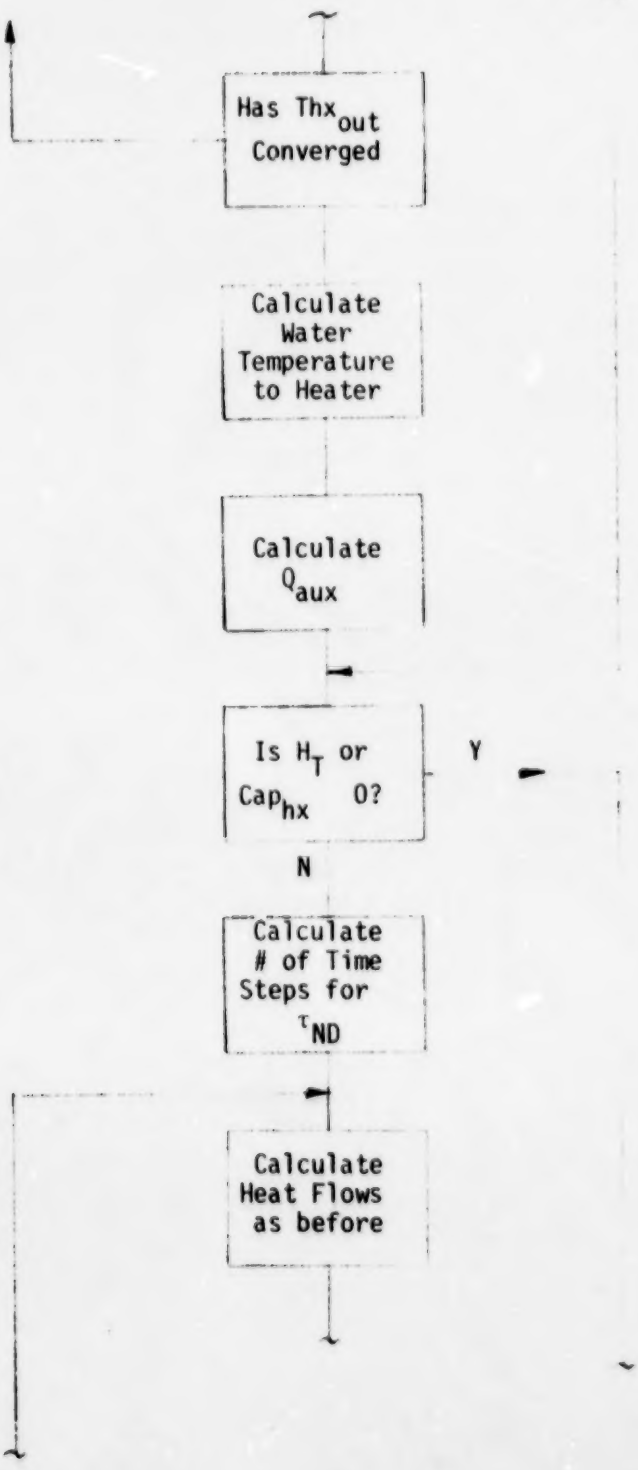
$$T_{ci} = T_{hxo} - \frac{Q_{loss}}{\dot{m}Cp}$$

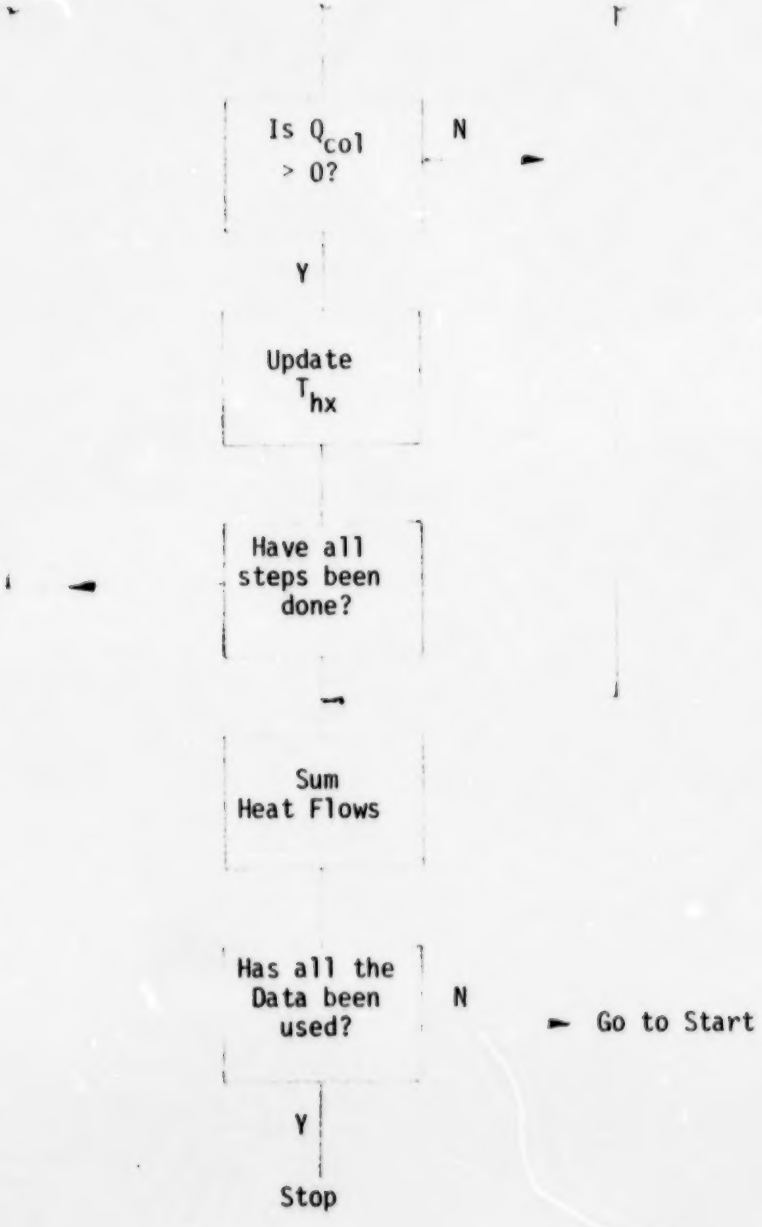
where Q_{loss} is the heat loss from the collector supply pipe.

Figure 5.2: Program Flow Chart for System 2




Calculate T_{ci}
Calculate Q_{col}
Is Q_{col} 0 ?
N
Calculate Q_{loss} for Collector Return Pipe
Calculate Thx_{in}
Calculate Thx_{out}


Has Thx_{out} Converged
Calculate Water Temperature to Heater
Calculate Q_{aux}
Is H_T or Cap_{hx} 0?
Y
N
Calculate # of Time Steps for τ_{ND}
Calculate Heat Flows as before


Is Q_{col} > 0?
N
Y
Update T_{hx}
Have all steps been done?
Sum Heat Flows
Has all the Data been used?
N
Go to Start
Y
Stop

The amount of heat collected is calculated as described in Section 5.1.1. The amount of heat transferred by the external heat exchanger is calculated as shown in Section 5.5. Because the temperature of the collector side fluid leaving the heat exchanger is not known at the beginning of the calculation, the program must iterate until the heat collected equals the heat transferred.

During the period of no water demand (τ_{ND}), the system continues to operate, provided heat can be stored in the heat exchanger. The temperature of the heat exchanger will continue to rise until it becomes equal to the collector stagnation temperature. The model for the transient operation of the heat exchanger is given in Section 5.5. The period of no water demand is divided into a number of steps as follows:

$$N_{step} = \frac{\dot{m}Cp}{Cap_{hx}}$$

where Cap_{hx} is the capacitance of the heat exchanger.

For each step the heat flows are recalculated and the temperature of the heat exchanger updated.

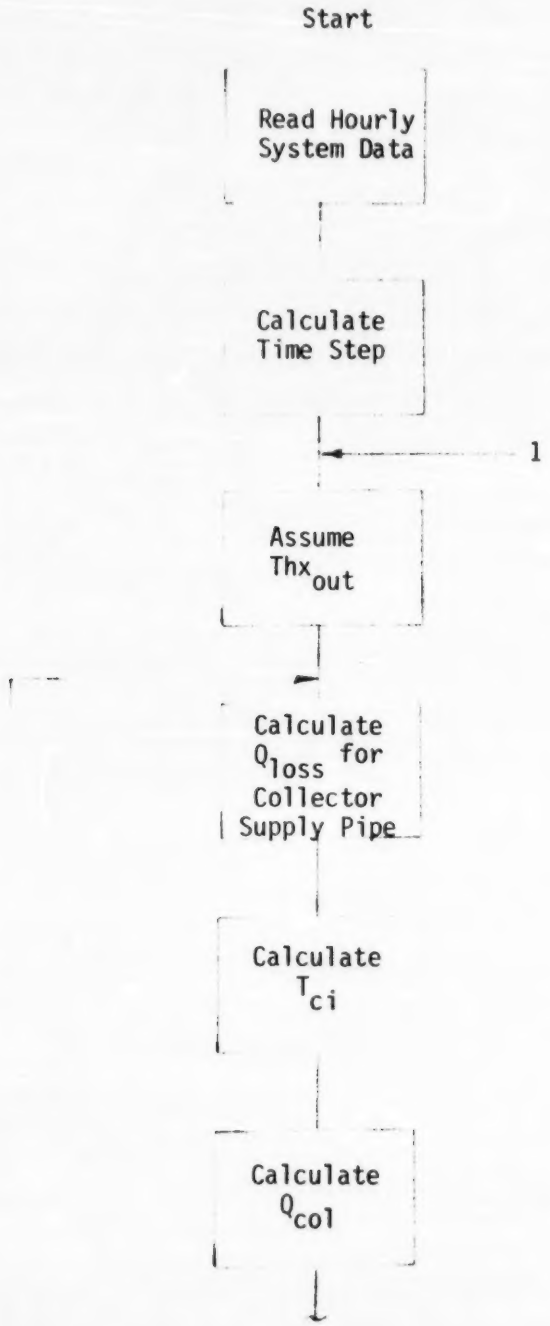
5.1.3 System 3 Overview

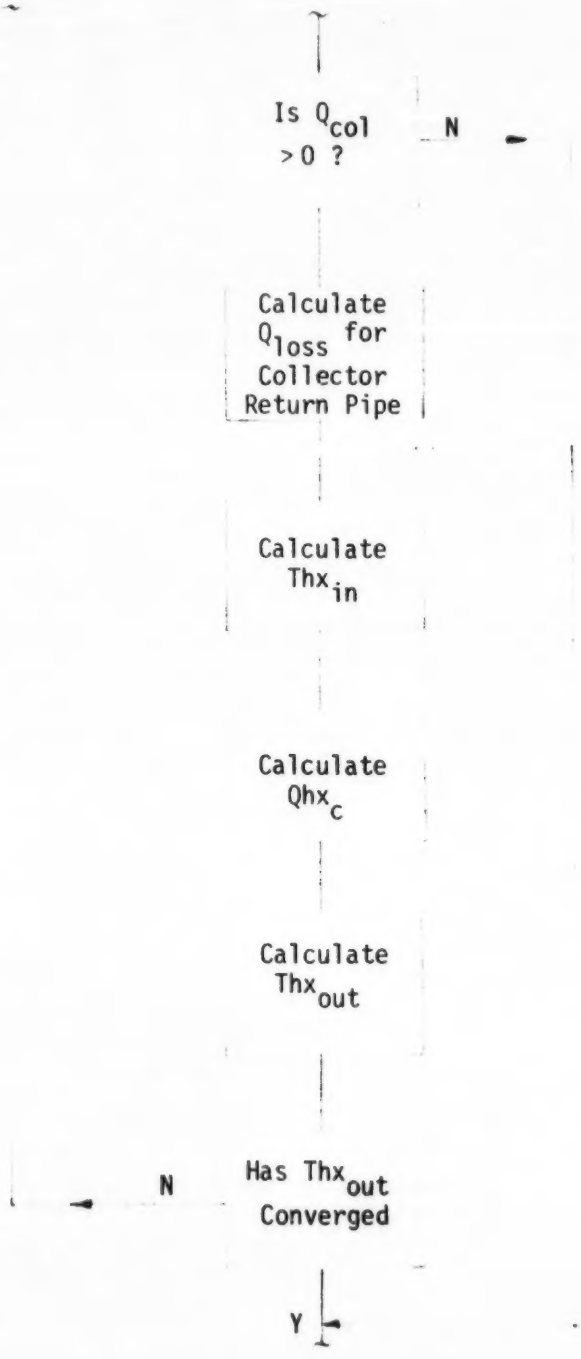
Because this system has a storage tank, the time step is not set according to water demand but is adjusted so that the maximum flow through the tank is less than the volume of a storage tank node.

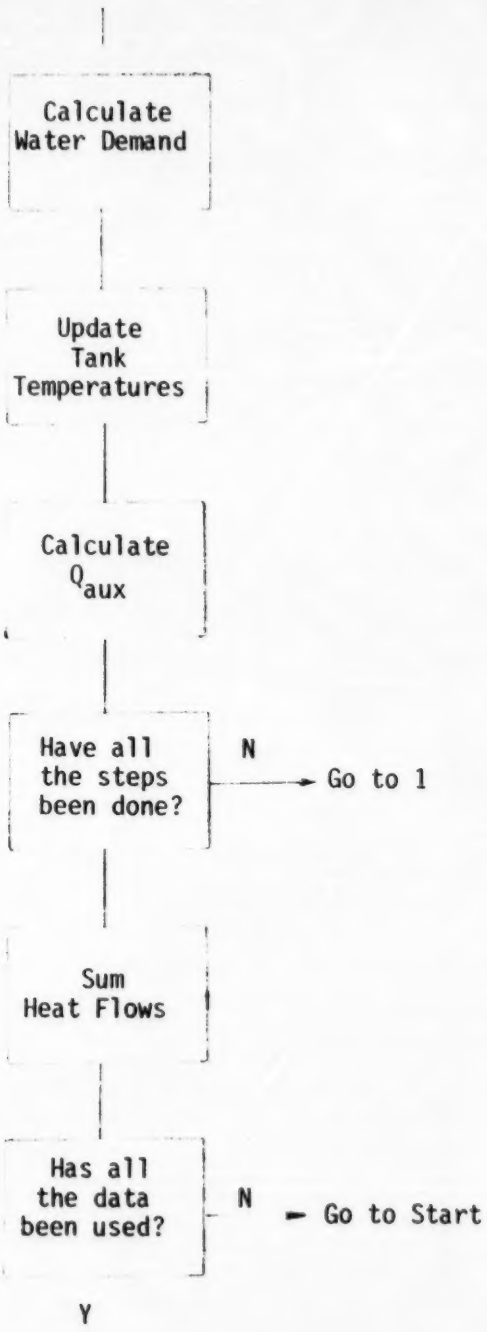
$$\tau = \left(\frac{Cap_{st}}{\dot{m}Cp_c}, \frac{Cap_{st}}{\dot{m}Cp_L}\right)_{min}$$

where Cap_{st} is the thermal capacitance of a storage tank node,
$\dot{m}Cp$ is the heat capacitance flow rate through the collector (subscript c) or to the load (subscript L).

Figure 5.3: Program Flow Chart for Systems 3 and 4




Is Q_{col} >0 ?
N
Calculate Q_{loss} for Collector Return Pipe
Calculate Thx_{in}
Calculate Qhx_c
Calculate Thx_{out}
Has Thx_{out} Converged
N
Y


Calculate Water Demand
Update Tank Temperatures
Calculate Q_{aux}
Have all the steps been done?
N
Go to 1
Sum Heat Flows
Has all the data been used?
N
Go to Start
Y

During each time step the heat collected and transferred to the storage tank is calculated. The calculation procedure is the same as described for System 2 except that an immersed coil heat exchanger model is used (see Section 5.4). As before this collector is iterative because the temperature out of the heat exchanger is not known initially.

When the heat transfer into the tank is known, the tank temperatures are updated. The method of calculating the change in temperature of the tank nodes (due to water demand and heat transferred from the immersed coil) is described in Section 5.3. The calculation of the auxiliary heat requirement is discussed in Section 5.7.

5.1.4 System 4 Overview

System 4 operation is the same as for System 3 except an external heat exchanger is used. In this system water flows into the tank from the city mains and the external heat exchanger. The external heat exchanger model is discussed in Section 5.5.

5.2 Solar Collector Model

Collector performance is estimated using the standard Hottel-Whillier-Bliss model of $F_R\tau\alpha$ and F_RU_L. The program assumes that these collector characteristics are independent of temperature and solar radiation. The values are adjusted, however, for heat capacitance flow rate.

$$F_R\tau\alpha(\text{adjusted}) = r \cdot F_R\tau\alpha(\text{test})$$

$$F_RU_L(\text{adjusted}) = r \cdot F_RU_L(\text{test})$$

$$\text{where } r = \frac{\dot{m}Cp\ (1 - \exp[-AF'U_L/(\dot{m}Cp)])}{(\dot{m}Cp)_T(1 - \exp[-AF'U_L/(\dot{m}Cp)_T])}$$

$$F'U_L = \frac{-(\dot{m}Cp)_T}{A}\ \ell n[1 - F_RU_L(\text{test})A/(\dot{m}Cp)_T]$$

For each hour, the reduction in solar transmission of the collector due to non-normal angles of incidence is calculated. The user enters five pairs of values of incidence angle and incidence angle modifier. The program estimates other values of incidence angle by cubic interpolation between points. The hourly incidence angle is calculated when the solar radiation data is processed. The solar transmissions of the diffuse and reflected solar radiation components are modified as recommended by Brandemuehl and Beckman[1]. This reference gives equations for the average angle of incidence for diffuse and reflected solar radiation components. The incident angle correction is found by interpolating between the values input by the user (parameter C13).

The solar heat collected is given by:

$$Q_{col} = A_{col} * [(H_b * K_b + H_d * K_d + H_r * K_r) * F_R(\tau\alpha)_{adjusted} - F_R U_{L_{adjusted}} (T_{ci} - T_a)]$$

where A_{col} is the collector area,

H_b, H_d, H_r are the beam, diffuse and reflected solar radiation components,

K_b, K_d, K_r are the beam, diffuse and reflected incident angle modifier,

T_{ci} is the collector fluid inlet temperature,

T_a is the outdoor or ambient temperature.

5.3 Solar Storage Tank Model

Water storage tanks will exhibit some temperature stratification. The magnitude of the stratification depends on system flow rates and temperatures. The model used in the program is as recommended by Klein [2]. This model is similar to, yet more flexible than, the model given in Duffie and Beckman [3].

The tank is modelled as a series of vertically stacked nodes. A mass and energy balance is performed on the nodes for each time step. The water entering the tank (from either the load or the collector) is assumed to rise or fall to the node closest in temperature. If water is flowing from the load and the collector, the fluid streams are assumed fully mixed before they enter each segment. The energy balance on the tank also takes into account heat lost by each node to the environment.

A heat balance on a storage node gives:

$$T_{si}' = T_{si} + [\alpha_i \dot{m}_c C_p (T_{co} - T_{si}) + \beta_i \dot{m}_L C_p (T_{lo} - T_{si}) + Q_{hx} - Q_{loss} + Q_{up} + Q_{down}] / \tau(m_i C_p)$$

where T_{si} is the temperature of the node i at the beginning of the hour,

T_{si}' is the temperature of the node i at the end of the hour,

$\dot{m}_c$, $\dot{m}_L$ are the hourly mass flows from the collector and the load to the storage,

C_p is the specific heat of water,

m_i is the mass of the water in node i,

Q_{hx} is the heat transferred into the tank from collector and/or load side heat exchangers,

Q_{loss} is the amount of heat lost to the environment by conduction out the storage walls,

Q_{up}, Q_{down} is the amount of heat transferred into the node by flow coming up or going down,

τ is the time step,

α,β are control functions that define the node(s) where the fluid effectively returns.

The control functions are given by:

if $r_c \leq i \leq s_c$ or $s_c \leq i \leq r_c$

then $\alpha_i = 1 / (|r_c - s_c| + 1)$

otherwise $\alpha_i = 0$

if $r_L \leq i \leq s_L$ or $s_L \leq i \leq r_L$

then $\beta_i = 1 / (|r_L - s_L| + 1)$

otherwise $\beta_i = 0$

where r_c is the node number where the collector fluid returns,

r_L is the node number where the load fluid returns,

s_c is the node number to which the collector return fluid is closest in temperature,

s_L is the node number to which the load return fluid is closest in temperature.

The quantity Q_{down} is given by:

for $\gamma_i > 0$

$$Q_{down} = \gamma_i (T_{si-1} - T_{si})$$

where $\gamma_i = \dot{m}_c C_p \sum_{j=1}^{i-1} \alpha_j - \dot{m}_L C_p \sum_{j=1}^{N} \beta_j$

otherwise $Q_{down} = 0$

The quantity Q_{up} is given by:

for $\gamma_{i+1} < 0$

$$Q_{up} = \gamma_{i+1} (T_{si} - T_{si+1})$$

The mass of each node depends on the tank geometry and location of the collector supply and return pipe connections. The collector supply pipe is assumed to always exit at the bottom of a node, and the collector return pipe is assumed to always enter the tank at the top of a node. This makes the density variation in the tank sensitive to the location of the connections. When required, one fully mixed node is assumed above the return connection, and one below the supply connection is also assumed. The remainder of the volume between the supply and return pipe connections is divided into equally sized nodes.

The solar storage tank is assumed to be cylindrical in either the vertical or horizontal orientation. The calculation of the volume and UA value for each node is straightforward for the vertical tank. For the horizontal tank, calculation of the volume of the nodes above the return and below the supply pipe connections, and the UA value for each node, is complicated by the geometry.

The program allows input of the distance, h, from the top of the tank to the return connection (see Figure 5.4). Given this distance, the volume of the first or top node can be calculated from:

$$V_1 = L \times A$$

where V_1 = volume of the node (m^3),

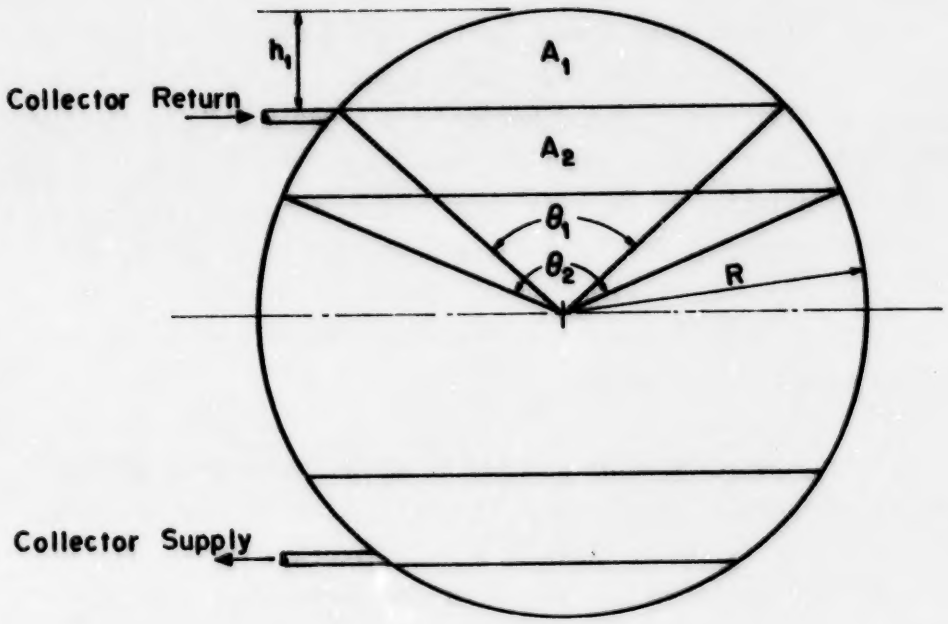
$A_1 = \frac{1}{2} R^2 (\theta_1 - \sin\theta_1)$,

L = length of tank (m),

R = radius of tank (m),

$\theta_1 = 2 \cos^{-1} (1 - h/r)$ (rad),

h_1 = distance from top of tank to return connection (m).



HORIZONTAL TANK END VIEW

Figure 5.4: Variable Definition for Horizontal Storage Tank

The heat transfer area for the first node can be calculated from:

$$A_{HT_1} = R\theta_1 - L + 2A_1$$

The volume and heat transfer area of the node below the collector supply connection are calculated in a similar manner. The remaining volume of the tank can be calculated by subtracting the volume above the return and below the supply connection from the total volume.

The tank surface area for the second node can be calculated from:

$$A_s = R(\theta_2 - \theta_1)\, L + 2A_2$$

where A_s = the tank surface area of node 2,
R = radius of tank,
L = length of tank,
A_2 = area at end of tank for node 2 = V_2/L.

The equation for θ_2 is:

$$\theta_2 - \sin\theta_2 = 2(A_1 + A_2)/R^2$$

This is an implicit equation which must be solved by iteration. The Newton-Raphson method for solving implicit equations is used in the program to solve the above equation.

All the remaining nodes are treated in the same manner. Once the volume and heat transfer area of each node is known, the mass and UA values can be easily calculated.

After the temperatures have been updated, two checks are made in the program. The first check is for storage temperature instability. If the temperature of a node is greater than the temperature of the one above it, it is assumed that density differences will cause perfect mixing of

these nodes. The second check is on the minimum allowable temperature. If the temperature of any of the nodes goes below the minimum allowable temperature, it is assumed that an auxiliary heater comes on. Because the heater is most probably placed in the bottom of the tank, the heated water will rise and cause a fully mixed tank. If the heater has to be used, a warning flag is printed.

5.4 Immersed Coil Heat Exchanger

The program calculates the heat transferred from the coil to each node of the storage tank (see Section 5.3 for storage tank model). The temperature at the exit from each node is determined from the quantity of heat transferred to the storage tank. Thus:

$$T_{hx_{i+1}} = T_{hx_i} - Q_{hx_c}/(\dot{m}Cp)$$

where Q_{hx} is the heat transferred from the circulating fluid to the storage tank.

$$Q_{hx_c} = \dot{m}Cp\ (T_{hx_i} - T_{si})\ \eta_{hx}$$

The efficiency of the heat exchanger is calculated using the NTU (number of transfer units) method as recommended by Sheaff [4].

$$\eta_{hx} = 1 - \exp(-NTU)$$

where $NTU = L_{hx}\ U_{hx}/(\dot{m}Cp\ N)$,

U_{hx} = the overall heat transfer coefficient per unit length of coil.

The assumption in this equation is that each of the storage tank nodes contains the same length of immersed coil. The only quantity not known in this equation is the overall heat transfer coefficient per unit length of coil. Unfortunately this quantity depends on the temperature

difference between the circulating fluid and the storage tank. Thus U_{hx} must be re-calculated for every time step. Assuming that the pipe wall offers little resistance to heat exchange:

$$U_{hx} = \frac{1}{\frac{1}{h_i \pi D_i} + \frac{1}{h_o A_{out}}}$$

where h_i is the convective heat transfer coefficient on the inside of the coil,

h_o is the convective heat transfer coefficient on the outside of the coil,

A_{out} is the area of the outside surface.

If the inside flow is laminar, the equation used to evaluate h_i is:

$$h_i = 3.66\ k/D_i$$

If the Reynolds number is greater than 6000, h_i is calculated by:

$$h_i = 0.023 * K * 1053. * Pr^{1/3}/D_i$$

For Reynolds number between 2000 and 6000, linear interpolation is used to estimate h_i.

The outside heat transfer coefficient is a difficult quantity to estimate. The most commonly used equation for free convective heat transfer from pipes is:

$$h_o = 0.53\ k\ \left(\frac{g\ \beta(T_w - T_s)}{\nu^2\ D_o}\ Pr\right)^{.25}$$

Since the fluid on the outside of the coil is always water, the thermal properties contained in the above equation can be lumped into one term:

$$h_o = 0.53\ P\ (g\ (T_w - T_s)/D_o)^{0.25}$$

where P is the combined thermal properties.

For water, Sheaff [4] has recommended the following equation for P (in metric units):

$$P = 1. /(0.0022 + 0.233/[(\frac{T_w + T_s}{2}) + 13)]$$

For unfinned immersed coil heat exchangers:

$$A_{out} = \pi D_o$$

Many of the immersed coil heat exchangers have a finned outer surface to increase the heat transfer surface area. For these heat exchangers:

$$A_{out} = \pi D_o (1 - t_{fin} N_{fin}) + A_{fin} \eta_{fin} N_{fin}$$

where t_{fin} is the thickness of the fin,
N_{fin} is the number of fins per unit length,
A_{fin} is the surface area of a fin,
η_{fin} is the fin efficiency.

The surface area of an annular fin is:

$$A_{fin} = \pi[(D_o + 2L_{fin})^2 - D_o^2]/2 + \pi (D_o + 2L_{fin}) t_{fin}$$

The fin efficiency is a measure of the effectiveness of the fin in transferring heat. For an annular fin, fin efficiency is a complex equation containing Bessel functions. Evaluation of this equation would require considerable program execution time. A simple, yet reasonable, approximation to the equation for fin efficiency was found to be:

$$\eta_{fin} = 1.1316 - 0.3122 C_{f1} h_o^{\frac{1}{2}} - 0.0597 C_{f2}$$

provided that $0. < \eta_{fin} < 1.0$

where C_{f1} and C_{f2} are constants depending on fin shape and material.

$C_{f1} = (L_{fin} + t_{fin}/2) \cdot [2/(L_{fin} t_{fin} k_{fin})]$

$C_{f2} = (2L_{fin} + D_o + t_{fin})/D_o$

5.5 External Heat Exchanger Model

The steady-state performance of external heat exchangers is estimated using the effectiveness method. The user enters a heat exchanger effectiveness at specific shell and tube flow rates. The program calculates the heat exchanger heat transfer coefficient.

i) for parallel flow

$$UA_{hxp} = \frac{-C_{min} \ln (1 - X1E)}{X1}$$

ii) for counter flow

$$UA_{hxc} = \frac{-C_{min} \ln \left\{ \frac{1 - E}{1 - \frac{C_{min}}{C_{max}} E} \right\}}{X2}$$

iii) for counter-parallel flow

$$UA_{hx} = (UA_{hxp} + UA_{hxc}) / 2$$

where C_{min} is the minimum heat capacitance flow rate,
E is the heat exchanger effectiveness,
C_{max} is the maximum heat capacitance flow rate,

$$X1 = 1 + \frac{C_{min}}{C_{max}}, \qquad X2 = 1 - \frac{C_{min}}{C_{max}}$$

As is commonly done in the analysis of forced flow heat exchangers, the heat exchanger heat transfer coefficient is assumed constant (i.e independent of flow rate and temperature). For each time step, the heat exchanger effectiveness is re-calculated for the actual flow rates.

i) for parallel flow

$$E_p = \frac{(1 - Y_p)}{\left(1 + \frac{C_{min}}{C_{max}}\right)}$$

$$\text{where } Y_p = \exp\left(-\left(1 + \frac{C_{min}}{C_{max}}\right)\frac{UA_{hx}}{C_{min}}\right)$$

ii) for counter flow

$$E_c = \frac{(1 - Y_c)}{\left(1 - \frac{C_{min}}{C_{max}} Y_c\right)}$$

$$\text{where } Y_c = \exp\left(-\left(1 - \frac{C_{min}}{C_{max}}\right)\frac{UA_{hx}}{C_{min}}\right)$$

iii) for counter-parallel flow

$$E = (E_p + E_c) / 2$$

A key difference between the PROCESS program and other solar simulation programs is the inclusion of the capacitance of external heat exchangers. Under steady state conditions the heat transfer rate is given by:

$$Q_{ss} = E\, C_{min}\, (T_{hi} - T_{ci})$$

where T_{hi} is the heat exchanger inlet temperature - hot side,
T_{ci} is the heat exchanger inlet temperture - cold side.

The average steady state heat exchanger temperature is given by:

$$T_{hx} = \frac{C_h\, T_{hi} + C_c\, T_{ci}}{C_h + C_c}$$

At the start of the hour (or time step) the heat exchanger may not be at the steady state temperature but at some other temperature (T'_{hx}) defined by the system conditions in the previous time step. The amount of energy to be transferred from the heat exchanger to achieve steady state is:

$$Q_T = mCp_{hx} (T'_{hx} - T_{hx})$$

where mCp_{hx} is the capacitance of the heat exchanger.

The average rate that this heat is transferred to the fluid is:

$$q_T = C (T'_{hx} - T_{hx}) / 2$$

where C is the heat capacitance flow rate of the cold side if $T'_{hx} > T_{hx}$ or the hot side if $T'_{hx} < T_{hx}$.

The program time step can be split into two parts: transient heat exchanger operation and steady state operation. The length of time for transient operation is approximated as:

$$\tau = \frac{Q_T}{q_T}$$

The amount of energy transferred during transient operation is:

i) if $T'_{hx} > T_{hx}$

$$Q_h = Q_{ss}$$
$$Q_c = Q_{ss} + q_T \tau$$

ii) if $T'_{hx} < T_{hx}$

$$Q_h = Q_{ss} + q_T \tau$$
$$Q_c = Q_{ss}$$

where τ cannot be greater than the time step.

5.6 System Piping Model

There are two pipes for which heat loss must be calculated: collector supply and collector return. Assuming a linear fluid temperature drop and no thermal capacitance, the heat loss rate is given by:

$$T_{out} = T_{in} - Q_{loss}/(\dot{m}Cp)$$

$$\text{where } Q_{loss} = \frac{UA_p\ (T_{in} - T_a)}{1 + UA_p/(2\dot{m}Cp)}$$

A check is necessary on the outlet temperature to ensure that it does not go below the ambient temperature. The above equations are evaluated for the indoor and outdoor section of each pipe.

5.7 Auxiliary Tank Model

The auxiliary tank is modelled as being of uniform temperature (fully mixed). The minimum temperature of the auxiliary tank is the hot water set point temperature. If the water temperature entering the auxiliary tank is below the set point temperature, the auxiliary heater comes on. It is assumed that the auxiliary heater can instantaneously heat the water to the desired hot water temperature.

Total tank heat loss to the surrounding environment is calculated for each time step and auxiliary heat is added if necessary to maintain the desired temperature.

This model can be written as follows. The heat removed from the tank is:

$$Q_{loss_a} = UA_a\ (T_{aux} - T_{sur})$$

$$Q_{out} = m_L\ C_p\ (T_{hot} - T_{t_{out}})$$

where Q_{loss_a} is the heat lost to the environment by conduction from the storage tank,

Q_{out} is the heat removed because of the difference in temperature between inlet and outlet water.

The new auxiliary tank temperature as a result of these heat losses is:

$$T_{aux}' = T_{aux} - (Q_{loss_a} + Q_{out})\ \tau/C_{aux}$$

The auxiliary energy (Q_{aux}) required to raise the tank temperature to the desired hot water temperature is:

$$Q_{aux} = (T_{hot} - T_{aux}')\ C_{aux}/\tau$$

5.8 Water Load Model

Because most solar industrial process water heating systems are used to heat city mains water, the hot water demand model has been set up to easily simulate this type of load. The water demand can be varied on an hourly basis for two different schedules. The first schedule is for the water demand during the first part of the week. The second schedule is for the water demand in the remainder of the week. The total water demand for each week is assumed constant.

The mains water temperature usually varies throughout the year. Regardless of its initital temperature, city mains water assumes the temperature of the ground surrounding the water pipe. The temperature of the ground depends on location, time of year and depth. An equation that represents the yearly fluctuation in ground temperature is:

$$T_{mains} = \bar{T}_{mains} - (\bar{T}_{mains} - T_{m_{min}})\ \cos[(N_{day} - 60)/365]$$

where $\bar{T}_{mains}$ is the average mains water temperature for the year,
$T_{m_{min}}$ is the minimum mains water temperature for the year,
N_{day} is the day number of the year (Jan 1st = 1).

5.9 Solar Radiation Model

Most Canadian weather stations measure only total solar radiation on a horizontal surface. Most solar collectors, however, are tilted towards the sun to increase the incident solar radiation. The program determines hourly values of beam, diffuse and reflected solar radiation on the tilted surface and stores the total in a scratch file. The algorithm for converting horizontal solar radiation to tilted solar radiation is similar to the method used in Duffie and Beckman [3].

In order to estimate solar radiation on a tilted surface it is necessary to split the total measured horizontal solar radiation into its two components: beam and diffuse. It is possible to estimate the amount of diffuse solar radiation from the ratio of the measured solar radiation to the extraterrestrial solar radiation. If this ratio is low then the solar radiation must be mostly diffuse, if this ratio if high the solar radiation must be mostly beam.

When the beam and diffuse solar radiation components are known, standard geometric relationships can be used to estimate the solar radiation components on a tilted surface. When estimating solar radiation on a tilted surface a third component is introduced: reflected radiation. Reflected radiation can be estimated from the beam radiation and the ground albedo or reflectivity.

The program equations and execution procedure are given below.

At the start of each day the solar constant and the earth's solar declination are calculated. The solar constant is given by:

$$S_c = 4871.0\ (1. + 0.33 \cos\ (2\pi N_{day}/365))\quad \text{in KJ/(hr m}^2\text{)}$$

where N_{day} is the day nuber (Jan 1 is 1).

The earth's declination is given by:

$$\delta = \frac{23.45\ 2\pi}{360} \sin \frac{(2\pi\ (284 + N))}{360\quad 365} \quad \text{(in radians)}$$

These values are assumed constant for each day. All other calculations are made on an hourly basis.

The first step is to read measured values of horizontal solar radiation and ambient temperature. The program has been set up to read data directly from the weather tapes as supplied by Atmospheric Environment Service, and is general enough to skip files that are not needed.

The extraterrestrial solar radiation on a horizontal surface is calculated by:

$$H_{ex} = S_c \cos(\theta_z)$$

where $\cos(\theta_z)$ is cosine of the zenith angle (angle between the beam and the vertical,

$$\cos(\theta_z) = \cos(\phi) \cos(\delta) \cos w + \sin\phi \sin\delta$$

where ϕ is the latitude of the location,

w is the hour angle.

The diffuse solar radiation (H_d) can be estimated using a correlation by Orgill and Hollands [5]:

$$H_d = 0.1769\ H \qquad \text{if } 0.75 < K_T$$

$$H_d = (1.55699 - 1.84013\ K_T)\ H \qquad \text{if } 0.35 \leq K_T \leq 0.75$$

$$H_d = (1. - 0.248857\ K_T)\ H \qquad \text{if } 0.0 \leq K_T \leq 0.35$$

where H is the measured hourly solar radiation (from weather tape),

K_T is the ratio of measured solar radiation to the extraterrestrial solar radiation
$= H / H_{ex}$.

The beam radiation (H_b) is simply the total measured solar radiation minus the diffuse radiation:

$$H_b = H - H_d$$

The next step is to calculate the ratio of beam radiation on the tilted surface to that on the horizontal surface (R_b):

$$R_b = \cos(\theta_T) / \cos(\theta_z)$$

where $\cos(\theta_T)$ is the cosine of the angle of incidence of beam radiation, between the beam and the normal to the surface,

$$\cos(\theta_T) = \sin(\delta)\sin(\phi)\cos(s) - \cos(\delta)\cos(\phi)\cos(s)\cos(w) + \cos(\delta)\sin(\phi)\sin(s)\cos(\gamma)\cos(w)\cos(\delta)\sin(s)\sin(\gamma)\sin(w)$$

γ is the azimuth angle measured from south (east is positive, west is negative).

Thus, the beam solar radiation on the tilted surface is:

$$H_{bT} = R_b H_b$$

The diffuse solar radiation component on the tilted surface is estimated using the radiation view factor from the collector to the sky with correction factors for non-uniform distribution of diffuse radiation.

The correction factors for anisotropic diffuse radiation are taken from Temps and Coulson [6] and Klucher [7]. The resulting equation is:

$$H_{dT} = \left(\frac{1 + \cos(s)}{2}\right)(1 + F \sin^3(s/2))(1 + F \cos^2(\theta_T)\sin^3(\theta_z))H_d$$

where $F = 1 - (H_d/H)^2$

The reflected solar radiation on the tilted surface (H_r) is:

$$H_r = \left(\frac{1 - \cos(s)}{2}\right)\rho\ H$$

where ρ is the ground reflectivity.

The total solar radiation on the tilted surface (H_T) is the sum of the beam, diffuse, and reflected solar radiation components.

Hourly values of beam, diffuse and reflected solar radiation on a tilted surface, ambient temperature, and angle of incidence are written to the scratch file. When all the data have been processed and written to the scratch file, the file is rewound, ready for the system simulation.

6. PROGRAM SETUP

Six file definitions must be made before the program can be run:

Terminal (Read) - (Unit 5) is the device used for data input. The program will send all questions and prompts to this device.

Printer - (Unit 7) is the device that receives the printed output (i.e. a printer). If a send and receive printer is being used unit 7 need not be defined.

Weather Data - (Unit 1) is the file containing the TRNSYS compatible weather data. The data must be written in the format (2X, I2, 2X, I2, 2X, I2, F3.1, I3, F6.1) and contain month number, day number, hour number, ground reflectivity, ambient temperature (°C), and solar radiation on a horizontal surface (W/m^2).

Processed Data - (Unit 9) is the file that is created by the program containing the solar radiation on the tilted surface and ambient temperature.

Terminal (Write) - (Unit 6) is the device that receives questions from the program concerning the input of data.

Default Data - (Unit 4) is the file containing program default data.

The PROCESS program is written in FORTRAN 77. In order to compile this program on your system, it must be able to handle this improved version of FORTRAN.

7. REFERENCES

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3. Duffie, J.A. and W.A. Beckman, Solar Engineering of Thermal Processes, Wiley Interscience, New York, 1980.

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6. Temps, R.C. and K.L. Coulson, Solar Energy, Vol. 19, No. 2, "Solar Radiation Incident upon Slopes of Different Orientation".

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MAP
Canadian Weather Stations
Resolute
Frobisher Bay
Uranium City
Churchill
Prince George
Edmonton
Vancouver
Victoria
Summerland
Medicine Hat
Swift Current
Saskatoon
The Pas
Winnipeg
Brandon
Kapuskasing
Thunder Bay
Val d'Or
Goose Bay
Gander
St. John's
Stephenville
Sept. Iles
Riviere du Loup
Bagotville
Quebec
Charlo
Chatham
Fredericton
Saint John
Sydney
Charlottetown
Moncton
Truro
Halifax
Yarmouth
Sherbrooke
Montreal
Sault Ste. Marie
Sudbury
Ottawa
Muskoka
Kingston
Toronto
London

City	Province	Latitude (Deg.)	Year	Solar Rad. Derived/Measured
Victoria	B.C.	48.7	1971	D
Prince George	B.C.	53.9	1974	M
Vancouver	B.C.	49.2	1971	M
Summerland	B.C.	49.6	1971	D
Frobisher Bay	N.W.T.	63.8	1975	D
Resolute	N.W.T.	74.7	1971	M
Edmonton	Alta.	53.6	1971	M
Medicine Hat	Alta.	50.0	1971	D
Uranium City	Sask.	59.6	1971	D
Swift Current	Sask.	50.3	1971	D
Saskatoon	Sask.	52.2	1971	D
Churchill	Man.	58.8	1975	D
Brandon	Man.	49.9	1971	D
Winnipeg	Man.	49.9	1971	M
The Pas	Man.	53.8	1971	M
Thunder Bay	Ont.	48.4	1971	D
Sault Ste. Marie	Ont.	46.5	1971	D
Sudbury	Ont.	46.5	1971	D
Kapuskasing	Ont.	49.4	1966	M
Kingston	Ont.	44.2	1971	D
Muskoka	Ont.	45.0	1971	D
Windsor	Ont.	42.3	1971	D
London	Ont.	43.0	1971	D
Toronto	Ont.	43.7	1971	M
Ottawa	Ont.	45.4	1971	M

Montreal	Que.	45.5	1971	M
Sept. Iles	Que.	50.2	1974	M
Quebec	Que.	46.8	1971	D
Sherbrooke	Que.	45.4	1971	D
Riviere du Loop	Que.	47.8	1971	D
Bagotville	Que.	48.3	1971	D
Val D'Or	Que.	48.0	1971	D
Fredericton	N.B.	45.9	1971	M
Charlo	N.B.	48.0	1971	D
Chatham	N.B.	47.0	1971	D
Moncton	N.B.	46.1	1971	D
St. John	N.B.	45.3	1971	D
Charlottetown	P.E.I.	46.3	1971	D
Truro	N.S.	45.4	1971	D
Halifax	N.S.	44.7	1971	M
Sydney	N.S.	46.2	1971	D
Yarmouth	N.S.	43.8	1971	D
St. John's	Nfld.	47.6	1971	M
Gander	Nfld.	49.0	1971	D
Stephenville	Nfld.	48.5	1971	D
Goose	Nfld.	53.3	1971	M

POOR

QUALITY

ORIGINAL